CHARACTERISTICS OF A RECORD BREAKING HEAT WAVE AND MONSOON EVENT IN SOUTHERN CALIFORNIA DURING THE SUMMER OF 2006

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INTRODUCTION

On 24 June 2006 the large scale flow over southern California (Fig. 1) shifted from the usual dry westerly flow to an "east-west ridge to the north" pattern, with strong easterly flow (Fig. 2). This shift persisted through July, resulting in some all time record high temperatures, minimum temperatures near all time record high levels, and very high relative humidity and dewpoint values. July 2006 was the warmest month in history at the University of California, Riverside (near KRAL) which peaked at an all-time high temperature of 117 degrees F (Fig. 3). There were 2 large spikes (minima) in the surface pressure gradient magnitude, and the 24 hour pressure gradient trend (Fig. 4) corresponding to the warmest days at the coast. Easterly wind below canyons and passes accompanied the spikes. Sea surface temperatures peaked at 80 degrees F at Huntington Beach (Fig. 5). The remnants of tropical storm Emilia moved into southern California bringing warm, muggy conditions near the end of July. What made this pattern so unusual was the fact that during a typical June the relatively cool ocean temperatures, a strong onshore surface pressure gradient and strong upper level high pressure creates a moderately strong inversion (about 8-9 degrees C). This results in persistent night and morning low clouds west of the mountains with some episodes when the low clouds do not clear until afternoon, or linger all day at the coastline. Dry easterly flow, or a significant offshore pressure gradient (and/or pressure gradient trend), tend to lower the inversion, strengthening it, and making the low clouds more persistent at the coast. This results in cooler days near the coast, but warmer days inland. In 2006 the pattern shifted, beginning on 24 June, with an increase in moisture aloft and little overnight coastal low clouds or fog (a "disruption" of the normal pattern). There were numerous periods of mid level cloudiness, showers, and thunderstorms. Increased moisture aloft led to slower overnight radiational cooling in the boundary layer, less low clouds, and a higher starting point for the morning temperature run-up toward the afternoon highs.

The position of the upper level high was a key feature during this period. An upper level high over southern Nevada is a common scenario for generating heat waves during the summer (Atkin and Dandrea, 1998). During the 2006 event the high was stretched out along an east-west ridge axis. The strong easterly flow in the southern boundary of an east-west oriented high with occasions of offshore flow ("monsoonal offshore flow") has been shown to be a prolific producer of heat waves and easterly waves in the past (Small, 2004). Moisture is pulled from the Midwest, the Gulf of Mexico, and/or from Mexico itself. Upper lows that drop out of the westerlies in the center of the country (or resident in the tropical airmass) may drift west into southern California. Sometimes it is easier to see the weaker, retrograding upper lows in the water vapor imagery or the 300 mb maps. Dynamics associated with the upper level lows and easterly waves caught in the strong, persistent easterly flow aloft brought periods of thunderstorms to all areas at all hours of the day during the 2006 episode. This was different from the typical afternoon and evening thunderstorm pattern common in the mountains and deserts on days with weaker dynamics or a more "southerly" or weak easterly flow. Some severe thunderstorm activity occurred during this extended monsoonal episode, including the hottest day. The hottest afternoon was 22 July, when offshore flow (east winds at 18 knots) occurred at Ontario (KONT) with offshore surface pressure gradient conditions from the coast to the local deserts for classic "monsoonal offshore flow" conditions. These same winds resulted in a temperature jump back into the 90s shortly after midnight of the following night when the winds "resurfaced (near the top of the inversion in the foothills). What differentiates the 27 June and 22 July extreme heating cases from many June and July events that were not as "extreme" is the offshore flow and rather strong offshore trend. Instead of simply lowering and strengthening the inversion, the inversion was lowered to the surface and the sea breeze was delayed. When the sea breeze finally did develop, it was still a warm sea breeze. Near the end of the extended monsoon/heat wave event in late July the remnants of Tropical Storm Emilia brought boundary layer tropical moisture into the area. The rather high 850 mb dewpoints, clouds, and the warm sea surface temperatures kept air temperatures up overnight to just 2 degrees shy of the all time highest minimum temperature for a calendar day (76 degrees F versus 78 degrees F) at San Diego Lindbergh Field (KSAN) on 27 July. For the period from 0000 UTC 27 July 2006 to 0000 UTC 28 July 2006 the minimum temperature was 77 degrees F. Conditions finally trended toward normal by 31 July with coastal sea surface temperatures falling back into the 60s at Huntington Beach. In this TA we wish to examine some of the more interesting aspects of this episode.

GENERAL CHARACTERISTICS OF THE MONSOON

The monsoon season correlates almost perfectly with the days of summer, typically starting up about a week or so after the summer solstice in late June, and "shutting off" during the last couple of weeks of September, just after the fall equinox (there seems to be a minor time lag between them). August and September are the months most at risk for tropical storm remnants to move into the area. These remnants can drag monsoonal moisture offshore before the moisture moves over southern California in southwest flow. Sometimes upper level lows bring moisture that is not of a tropical origin into the area, especially at the edges of the monsoon season. During the middle of the monsoon season the vast majority of the moisture is tropical in origin. The key feature of the June 2006 pattern shift was the change from dry westerly flow off the ocean to a moist, unstable south and east flow off the land (due to the monsoonal high). This created many days with thunderstorms.

In order to compare the "Great Monsoon and Heat Wave Event of 2006" to the summers of 2003-2005 several curves were created. Figure 6 shows the percentage of days with thunderstorms in comparison to the "maximum 700-500 mb mean layer relative humidity of the day" on the Miramar (KNKX) California sounding. The data used for the initial calculations (the two lower curves indicated in blue) covers the months of June – September of 2003- 2005 (a total of 301 of a possible 305 days were available). The dataset for the 2006 monsoon/heat wave event encompassed the period of 1 June 2006 - 31 July 2006 (61 of a possible 61 days of data were available). The straight blue line is the trend line for the blue curve, showing a very high correlation of 0.91 for the initial data set. For the 2003-2005 period thunderstorms were reported on about 10 percent of the days when the 700-500 mb relative humidity reached about 30 percent.

For the purposes of this TA and based on the KNKX sounding, 30 percent 700-500 mb relative humidity with any wind in the layer with a direction from 0 to 225 degrees is defined as the lower bound for the "monsoon" designation in extreme southwestern California (a "stage 1 monsoon event"). At this value the monsoon is barely detectable and is in the form of cumulus developing over the mountains. Typically no thunderstorms form. It is possible to have thunderstorms at 700-500 mb mean layer relative humidity levels near 30 percent with sufficient dynamic support, but this is not common. A stage 2 monsoon event is when the relative humidity rises to 50 % or higher, and stage 3 is 70 % or higher. Based on the 2003-2005 curves (the 2 lower curves, in blue), subtracting 7 percent from the 700-500 mb relative humidity is a good first estimate for the probability of a thunderstorm. Above 65 percent relative humidity, thunderstorms are a good bet. The red curves are the curves for the "Great Monsoon and Heat Wave of Summer 2006". One interesting feature that stands out in the 2006 data is that there is a much higher incidence of thunderstorms for the same relative humidity values in comparison to the 2003-2005 initial curves. This may indicate more favorable conditions during the 2006 period due to factors such as wind direction from off the continent and the increased number of easterly wave and upper lows caught up in the "fast" easterly flow beneath the monsoonal high. On some days the thunderstorms simply developed over the higher terrain to the east and south, then "advected" into the forecast area. The high number of dynamically driven events in 2006 may also help to explain the reduction in the correlation coefficient in 2006. Monsoon-like patterns can occur when dynamics such as upper level lows move into the area from the west, and these events can easily cause thunderstorms anywhere with 700-500 mb relative humidity values in the 40 % with flow from any direction. They can also be very prolific producers of lightning. When the 700-500 mb mean layer relative humidity rises above about 70 %, there may be thunderstorms (or at least showers) in the coastal areas if there are clouds associated with it, with or without significant dynamics. If the dynamics are very weak, then typically the 50 % relative humidity level contour must fall to about 650 mb for thunderstorms to develop in the mountains.

BRIEF OVERVIEW OF THE EASTERLY WAVES

On 24 June 2006, early in the monsoon, a weak easterly wave went through the forecast area. The outflow rippled along the top of the marine layer carving out numerous holes and a myriad of gravity waves developed before clearing out the low clouds (Fig. 7 and Fig. 8). On the following day (25 June) a line of thunderstorms went through Rancho Bernardo (west of KRNM) associated with another easterly wave (Fig. 9). The temperature jumped from 85 at about 1130 AM to 101 at 1245 PM, back to 83 degrees F at 130 PM, and finally back up into the mid 90s for much of the remainder of the afternoon. Thus began the series of days with the standard marine layer pattern being strongly affected by easterly waves. On 27 June 2006 the waves in the low cloud pattern can be seen pulsating away from the islands as the waves propagated westward (Fig. 10 and Fig. 11). Winds gusted to about 50 mph with this easterly wave in Aliso Viejo, just south of the Santa Ana area (KSNA). There was little rainfall at the surface (if any). With the inversion pushed to the surface and weak pressure gradients, this easterly wave helped to bring the heating all the way to the coast with the highest temperature recorded in San Diego since 1989 (96 degrees F). In this case, strong surface winds were associated with the easterly wave. Convectively-generated wind events during warm season with no rainfall occasionally occur with a gust front from far off thunderstorms, (but are usually confined to the deserts). These winds can locally emerge below passes and canyons west of the mountains with reduced visibilities in blowing dust.

CONVECTIVE CHARACTERISTICS OF FLOW ALONG AND ACROSS A MOUNTAIN RIDGELINE

During "fast flow" days (with easterly winds 15 knots or more at around 500 mb and/or around 20 knots at 300 mb) thunderstorms generally develop during the afternoon over the highest peaks, and then drift downstream over the coastal waters and coastal areas. There may be additional enhancement if a thunderstorm tracks along the mountain ridgeline for continued mountain convergence and heating before drifting off the mountains (similar to what happens to convection in cold moist air flowing over a warm body of water). Ridge generated upward motion continues to act on the parcels as long as the parcels remain along the heated ridges. Parcels lose some lift as they drift off the mountains. The transverse ranges in the north (the San Bernardino County Mountains, including the eastern edge of the San Gabriel Mountains) have the best fetch of elevated terrain during easterly flow. It has been noted that the first day of a severe weather or flash flood pattern often occurs when the lower mid-level flow (about 850-700 mb) becomes nearly unidirectional from the south (about 160 degrees) at about 5 to 14 knots. This setup allows convection developing over the north-south mountain ranges to "ride the mountain ridgeline" northward. It seems that given the same amount of relative humidity aloft, flow along the mountains is a more conducive pattern to developing thunderstorms than flow across the mountains. With unidirectional flow the shear is reduced, especially if speeds are relatively uniform in the vertical. Southerly flow seems to be the best direction for the north-south ranges from the mountains just south of the Mexican Border to the San Bernardino County Mountains. These storms often drift north off the mountains and into the Apple and Lucerne Valleys. After the winds shift from southerly (which is the best direction for "ridge riding") to become more perpendicular to the north-south oriented ranges, there is usually a drop off in the strength of the convection. This is especially true if the shift is to a westerly flow. A drop off is also common after the winds rise to 15 knots or higher. The "elevated fetch" on the mountains oriented in the east-west direction is much smaller than the elevated fetch in the north-south direction. This may help to explain the explosion of convection on 28 June, after the switch to southerly flow (figures 12 and 13) in comparison to the fast easterly flow days of 23-26 June. [It should be noted that the winds aloft were also lighter on 28 June and could have added to the strengthening of the convection, since pulse type convection is the dominant convective type in southern California during the warm season (Small, 2004)]. When the moisture works its way lower in the atmosphere as the monsoon matures, a perpendicular upslope flow near the surface can become at least as important as a parallel flow aloft. More work is planned on the topic of "ridge parallel flow aloft" in the future

One of the reasons why the storms die on the ridgelines and become more prevalent over the deserts during the late afternoon is the sea breeze finally clears the ridgeline of much of its strong heating, but sea breeze "arcs" and other boundaries prevail in the deserts. This often results in the "last gasp" storms on the arcs and other boundaries in the deserts, which can be the strongest convection of the day. When the "door is open to the east" with a continued stream of easterly waves or just one big low, (figure 14) the convection can occur anywhere and anytime since it is no longer tied to afternoon heating. Convective strength is usually limited until the winds aloft decrease to below 15 knots. A key feature of figure 14 is the 500 mb high strength, reaching a massive 6000 meters. This "east-west ridge axis to the north" pattern placed southern California in deep easterly flow and kept the door open to easterly waves. The upper low/inverted trough was clearly evident guiding easterly waves through southern California. Each easterly wave can bring an increase in the northeast to east flow, followed by a slacking off of and veering of the winds to southerly behind each wave. Since most of the summertime severe weather and flash flood events occur with rather light winds the easterly waves tend to keep the storms moving rapidly and somewhat sheared apart. As a result, the severe weather and flash flooding threat is somewhat reduce during periods dominated by rapidly moving easterly waves. This seems to change dramatically to a more severe/flash flood scenario when the winds become more southerly, and especially if the winds weaken.

Figure 15 shows the transition of the sounding from the "all time record high temperatures" profile to a day dominated by tropical moisture in the boundary layer. The shift shows how tropical the sounding at the Miramar (KNKX) upper air site became as the remnants of tropical storm Emilia arrived. Figure 16 shows the arrival of the remnants of Emilia along with a comparison of the soundings from Miramar, California (KNKX), San Juan Puerto Rico (TJSJ) and Lihue (PHLI on the island of Kauai, Hawaii) at 1200 UTC 28 July 2006. The soundings all have approximately the same inversion height (about 800 mb). The San Diego Miramar sounding is actually wetter than the Lihue sounding in Hawaii. The San Juan sounding is the wettest in the boundary layer. All 3 soundings show easterlies above the inversion. Below the inversion, the KNKX sounding shows westerly onshore flow, which may have a tendency to be enhanced due to the warm inland conditions enhancing the onshore flow.

DISCUSSION AND CONCLUSION

The exceptionally strong monsoon/heat wave episode in 2006 began in late June and ended in late July, and disrupted the typical marine layer pattern. The absence of low clouds allowed record breaking heat to develop. Combined with the absence of northwest flow/upwelling over the inner coastal waters, water temperatures rose locally to 80 degrees F. Easterly waves helped to disrupt the marine layer with the associated subsidence, lowering the inversion. By mid-July an upper low brought a tropical airmass and the associated elevated dewpoints to all areas (not just to the mountains and deserts as seen during a typical monsoon period), accompanied by strong easterly flow and a parade of easterly waves. By 22 July weak to offshore pressure gradients and trends along with subsidence behind an easterly wave resulted in all time record temperatures and heat indices of between 115 and 120 degrees in populated areas west of the mountains. Values were over 120 in the deserts. The 99 degree F reading in San Diego was the highest temperature since 1989. Due to temperatures near 36 degrees C (97 degrees F) at the inversion top, some low temperatures in the foothills near the inversion top only dropped into the mid 80s just before midnight, but then rose to around 94 degrees as gusty easterly flow surfaced at 2 am local standard time on 23 July 2006.

The subsidence associated with easterly waves over the coastal areas/waters, (especially with weak pressure gradients to the local deserts and offshore pressure gradient trends), can suppress, or even wipe out the marine layer with strong heating. Easterly waves helped modulate the amount of patchy low clouds and heating, as well as the timing of the thunderstorms. If the models indicate subsidence from an easterly wave near the coast at a time of weak surface pressure gradients, fairly strong offshore pressure gradient trends (and a low level downward vertical velocity maximum also helps), temperatures may rise higher than is expected by the forecaster or the model guidance, and may reach adiabatic temperatures (T850 + 26 F) over the coastal plain. Gradients were more north-south oriented, similar to 26-27 June 1991 (Ryan, 1996) when many record high temperatures fell in southern California. Conditions typically go from little or no strong thunderstorms, to strong to very strong thunderstorms when the mid level west wind switches to south or south-southeasterly with a light to moderate speed (seems to prefer speeds between 5 and 15 knots). In these cases the storms "ride the ridgelines" (for example 28 June). When the northwest flow and upwelling finally re-developed, sea surface temperatures at Huntington Beach fell rapidly from 80 degrees to the upper 60s in less than 48 hours. Although rather warm mid to late summer water temperatures help allow clearing of the beaches each afternoon, the cool water temperatures can have some effect on the lower clouds as it may help cool the boundary layer and strengthen the inversion. This can make the low clouds last longer into the afternoon (as is the case in the spring) with additional cooling. The low clouds were held at bay during much of the monsoon until former tropical storm Emilia advected clouds in below 6500 ft MSL.

And finally, heat waves lasting several days are a part of nearly every summer over southwest California, but due to the proximity to the cool Alaskan Current, they are usually tempered, and rarely have a lasting effect along the coast (especially during the early summer). What made this event so unusual and extreme was that it lasted over a month and it occurred when climatology favors a dependable, moderating onshore flow of marine air (caused mainly by the temperature differential between the hot deserts and cool ocean waters). The high sun angle heats the deserts to their warmest values in July (maximum solar insolation and longest days). The marine layer modulates the heating near the coast. This helps to delay the warmest days near the coast until August (and in some places until September), when the warmer water temperatures, moisture aloft (at times), reduced onshore pressure gradient, strong high pressure aloft, and periods of offshore flow combine for a less persistent marine layer and stronger heating.

While strong high pressure aloft is key for many heat waves, we have demonstrated that it was a combination of factors that made this heat wave exceptional. The key factors include:

1) Persistent high pressure at the surface and aloft over the western United States, resulting in a prolonged period of weak onshore flow, punctuated by days with strong offshore pressure gradient trends. Offshore trends of about -2.0 mb or more are considered strong for summer when gradients to the local deserts are weak. (Near neutral surface pressure gradients to the local deserts to the north, and about 3 mb or less onshore pressure gradients to the local deserts in the south are "weak").

2) An upper level high to the north oriented in such a way as to allow deep, moderate to strong east to southeast flow, preferably with at least 25 mph wind gusts below canyons and passes in southern California, for both mesoscale and synoptic scale subsidence. (Upper level highs with an east-west oriented ridge axis are especially prolific).

3) Easterly waves or upper level lows. (Preferably strong enough to produce convection, strong downward vertical motion, and gravity waves capable of scouring out the marine layer and/or pushing it out to sea).

4) Unusually weak seasonal northwest along-shore wind flow for an extended period which lessens coastal upwelling and allow surface water temperatures along the coast of southern California to rise to well above normal. High sea surface temperatures and/or high 850 mb temperatures can keep minimum temperatures at or above 70 degrees F west of the higher mountains, especially with sea surface temperatures in the mid 70s and 850 mb dewpoints are 10 degrees C or higher.

Any one or two of these features by themselves can create above normal temperatures over southwest California, however when combined, the heating is prolonged, maximized, and is likely to result in record-breaking heat.

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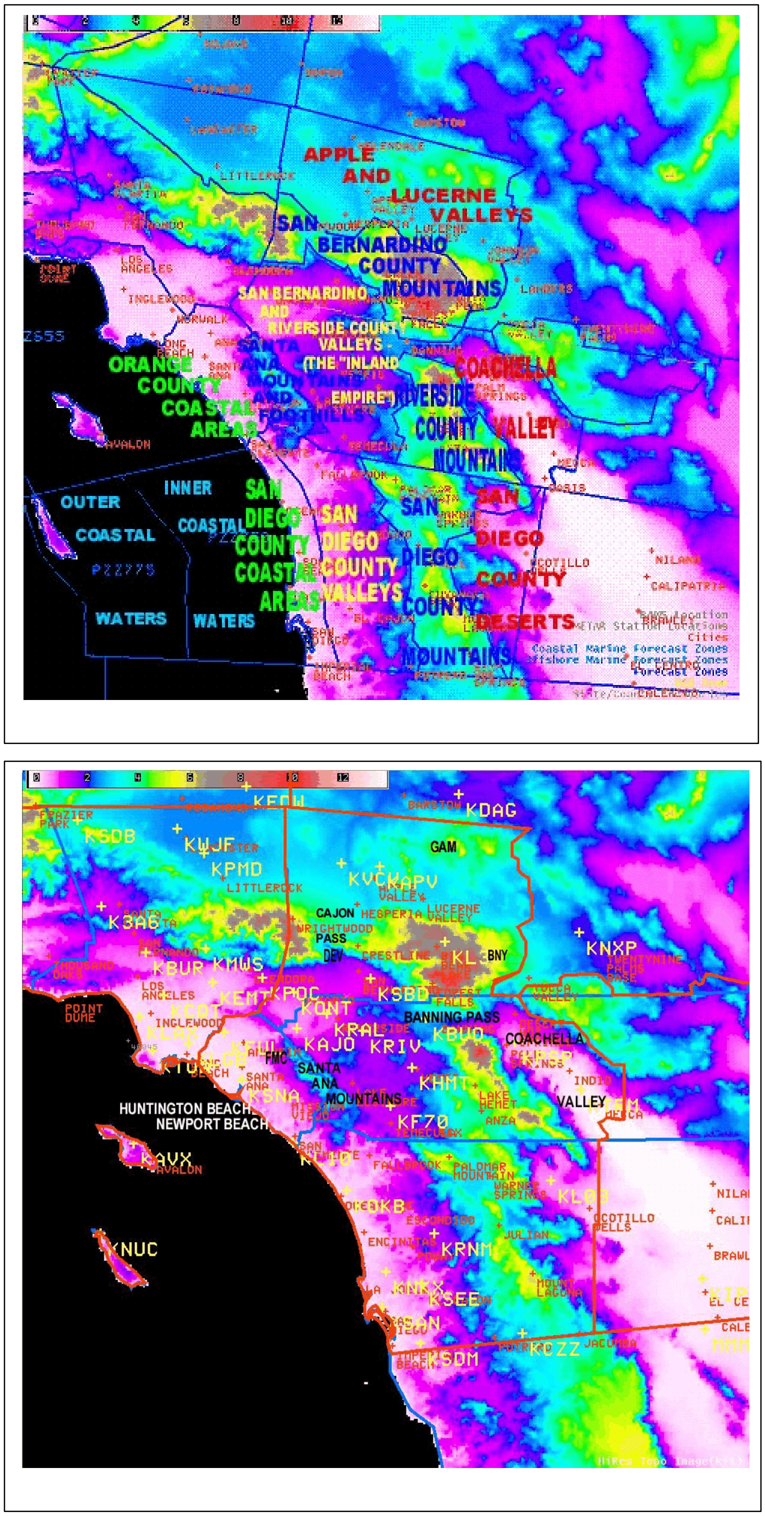

Fig. 1. Terrain maps of the WFO SGX County Warning and Forecast Area (CWFA). Color coding is in thousands of feet MSL.

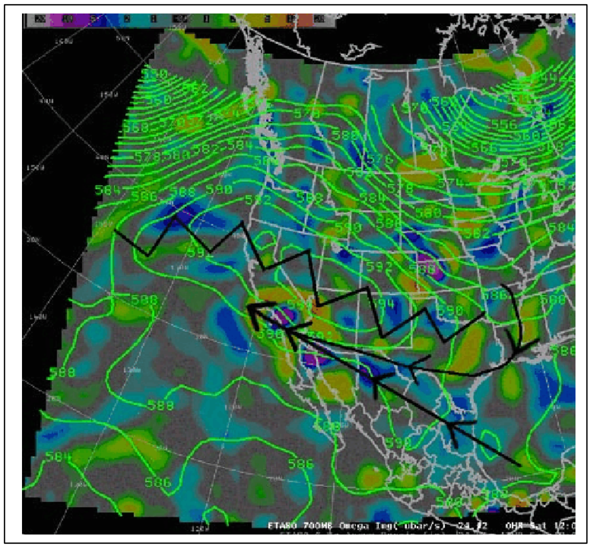

Fig. 2. The figure is the 00 hour 500 mb heights in decameters (green, solid) and the 700 mb vertical velocity in microbars per second (shaded) valid at 1200 UTC 24 June 2006 showing the east-west ridge axis pattern that persisted through July. Notice the tight packing of the height lines south of the upper high, allowing waves from the southeastern states, the Gulf of Mexico, and Mexico to be directed into southern California. The black arrows show the typical flow that can be expected with such a pattern. Well-defined waves (the orange/purple couplets of upward/downward vertical velocity) can be seen moving through southern California. Another couplet can be seen over western Kansas as a weak trough. The weak trough in the westerlies over Kansas may drop out of the westerlies into the easterly flow south of the ridge axis, and eventually move into southern California as an inverted trough.

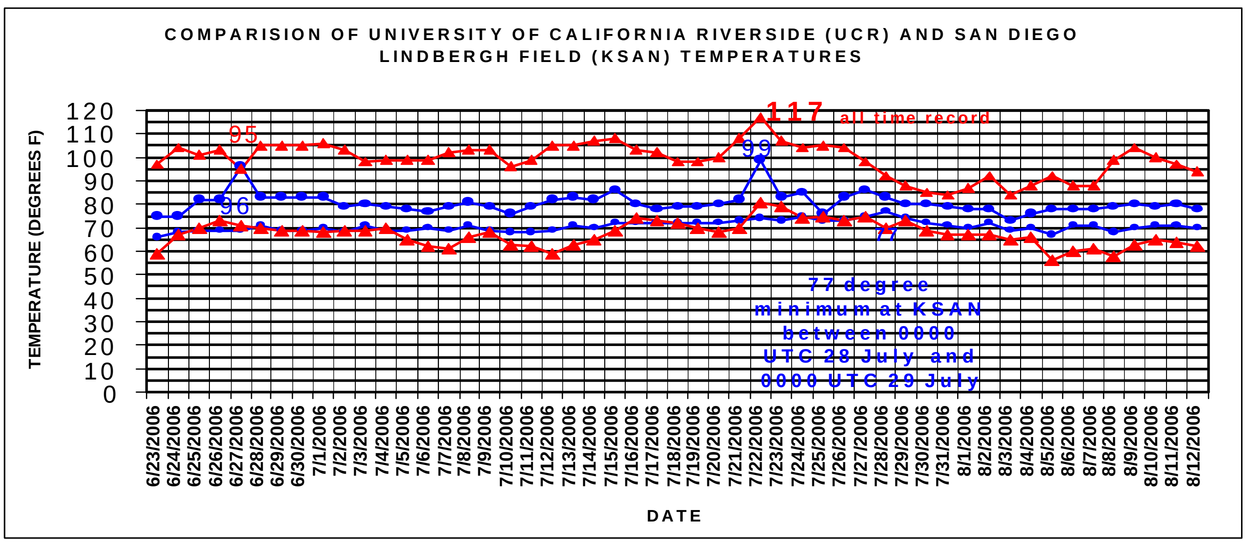

Fig. 3. The figure shows the high and low temperatures for the University of California Riverside (red with triangles) and San Diego Lindbergh Field (blue with circles). The temperatures are for the 24 hour period ending at 4 pm local standard time of the day in question. The peak San Diego temperatures of 96 and 99 degrees can be easily seen. The inversion top and 850 mb temperatures were 34.6 and 30.6 at 0000 UTC 23 July 2006. The overnight low temperature for the 24 hour period ending at 0000 UTC on 29 July 2006 was 77 degrees F. This 77 degree overnight low temperature occurred close to the sea surface temperature maximum of 80 degrees F at Huntington Beach at 1700 UTC 29 July 2006. (The all time record for a calendar day at KSAN is 78 degrees F). The strong modulating affect of the clouds on 27 June 2006 is reflected in the high temperature at San Diego (at the coast) exceeding the high temperature at Riverside (in the inland valley area), a rare event during the summer. Also, the extremely high 850 mb dewpoint peak was 15.6 degrees C at 0000 UTC 28, which helps to keep minimum temperatures up.

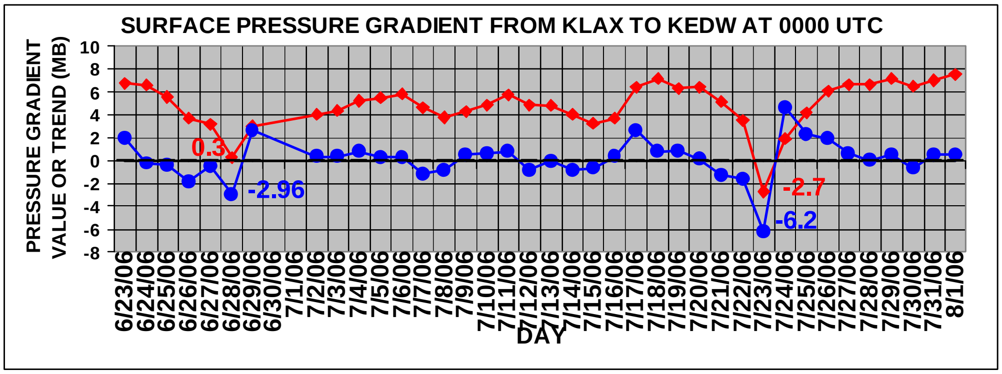

Fig. 4. The red curve with diamonds in the figure shows the 0000 UTC surface pressure gradient from Los Angeles International Airport at the coast (KLAX) to Edwards Air Force Base (KEDW) in the local deserts. (A "positive pressure gradient" denotes higher pressure at KLAX than at KEDW). The blue curve with the circles indicates the 24 hour pressure gradient trend (the 24 hour change in the pressure gradient). The pressure gradient usually shows a diurnal pattern consisting of a minimum in the pressure gradient in the morning and a maximum in the "positive" pressure gradient during the afternoon. The "dips" in the pressure gradient values at 0000 UTC 28 June 2006 and 0000 UTC on 23 July 2006 correlates well with the high temperatures in the upper 90s at San Diego. Normal surface pressure gradient trends are positive from morning to afternoon. In these cases, at 0000 UTC 28 June 2006 and 0000 UTC 23 July 2006, the pressure gradient trends were strongly negative on both days, even for the 24 hour period ending at 0000 UTC. Weak surface pressure gradients to the local deserts (3.0 mb or smaller) along with moderate offshore pressure gradient trends (approximately -2.0 mb) can easily result in strong heating to within about 10 miles of the coastline, and even out over the coastal waters at times.

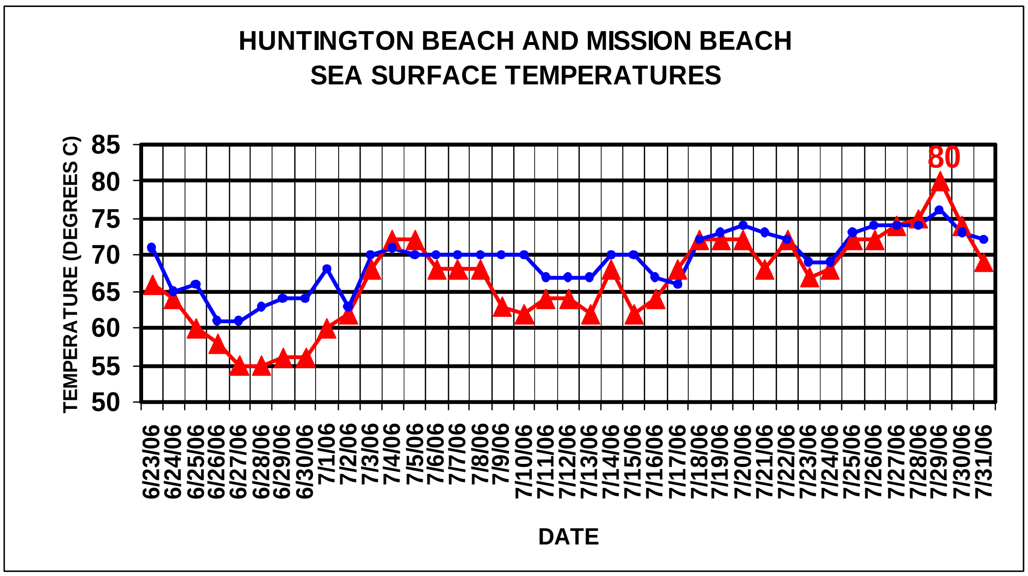

Fig. 5. Graph of the sea surface temperatures at Huntington Beach (near KSNA) and Mission Beach (near KSAN) at 10 AM PDT (1700 UTC). Water temperatures showed a general climb during the period to a peak of 80 degrees F by mid-morning on 29 July 2006. A rapid dive occurred at Huntington Beach thereafter, falling from the lower 80s to the upper 60s in about 48 hours as the upwelling returned.

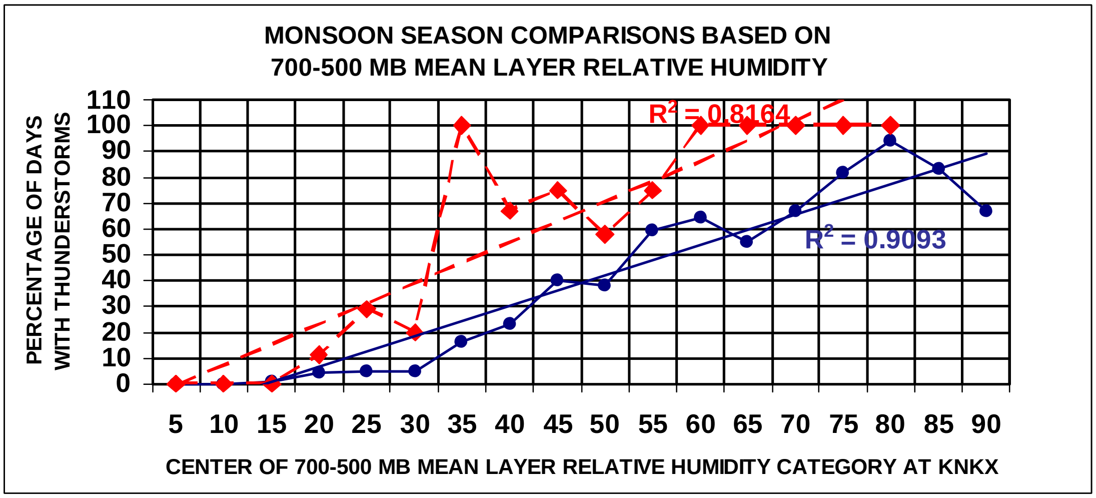

Fig. 6. Figure shows the percentage of days with thunderstorms in the WFO San Diego County Warning and Forecast Area (CWFA) in comparison to the maximum 700-500 mb mean layer relative humidity of the day at the Miramar (KNKX) sounding. The blue curve with the circles was constructed using the available data for June-September of 2003-2005 (Thunderstorm data was unavailable before summer 2003). A total of 301 of a possible 305 days were available. The blue line is the trend line for the curve, showing a very high correlation of 0.91. The dashed red curve with the diamonds and dashed trend line are for 1 June – 31 July 2006 (61 of a possible 61 days of data available). One feature that stands out is the curves for the 2006 event have a much higher incidence of thunderstorms compared to the 2003-2005 curves for the same relative humidity values. This may indicate more favorable conditions during the 2006 period due to factors such as wind direction from the continent and the increased number of easterly waves and upper low episodes caught up in the "fast" easterly flow beneath the monsoonal high. On some days thunderstorms beginning over the mainly higher terrain to the east simply "advected" into the forecast area. The high number of dynamically driven events may also help to explain the reduction in the correlation coefficient in 2006. For the purposes of this study the lower bound for an event to be labeled "monsoon" is 30 percent 700-500 mb relative humidity and any wind in the layer with a direction from 0 to 225 degrees. Notice that the 700-500 mb mean relative humidity and the percentage of days with thunderstorms is very similar based on the blue trend line for the 2003-2005 warm seasons. For this development data, the probability of a thunderstorm in the forecast area is slightly lower than the 700-500 mb layer mean relative humidity. (Simply reducing the 700-500 mb mean layer relative humidity by 7% is a good approximate of the probability of a thunderstorm as an initial estimate). The red curves are probably more applicable to a "dynamic" pattern with south (or possibly east) flow, and the blue curves are probably more applicable to a pattern with weak dynamics and south to east flow. For the "dynamic" cases, multiplying the mean 700-500 mb relative humidity by 1.5 is a good approximation of the probability of a thunderstorm. Typically, the most likely location of the first thunderstorms of the day (and sometimes the only area with thunderstorms) is the San Bernardino County Mountains, followed by either the San Diego County Mountains or the Apple and Lucerne Valleys. Only 3 years of data has been used for the blue curves, but they can still be used as a "reasonable estimate" of the character of the monsoon.

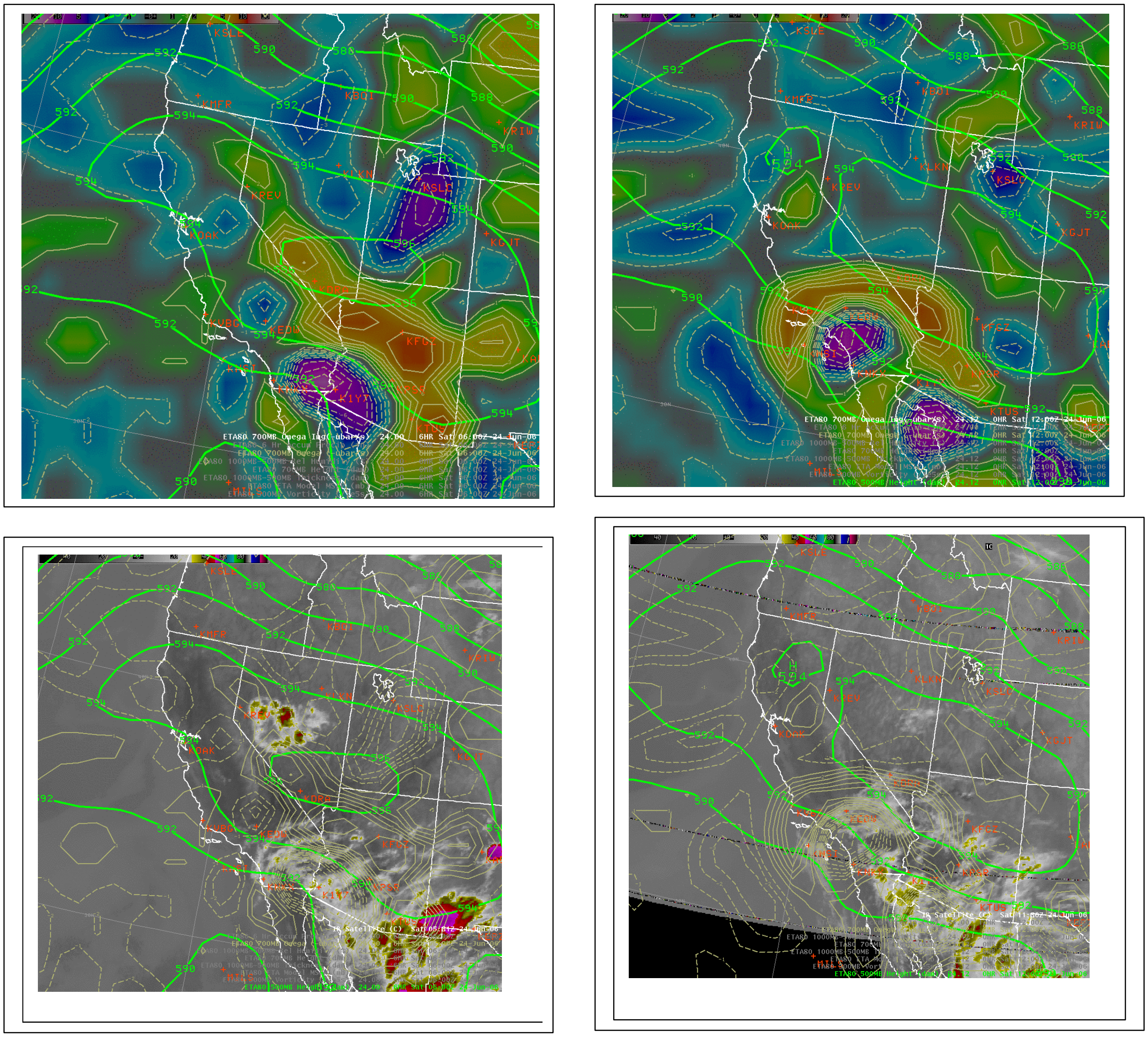

Fig. 7. The upper left panel is the 06 hour 500 mb forecast heights in decameters (green, solid) and the 700 mb vertical velocity in microbars per second (brown, dashed, and shaded) valid at 0600 UTC 24 June 2006. The upper right figure is the 00 hour 500 mb heights in decameters (green, solid) and the 700 mb vertical velocity in microbars per second (brown, dashed, and shaded) valid at 1200 UTC 24 June 2006. The lower left figure is the 0531 UTC infrared satellite imagery overlaid with the 06 hour 500 mb forecast heights in decameters (green, solid) and 700 mb vertical velocity in microbars per second (brown, solid and dashed) valid at 0600 UTC 24 June 2006. The lower right is the 1100 UTC 24 June 2006 infrared satellite imagery overlaid by the 00 hour 500 mb heights in decameters (green, solid) and the 700 mb vertical velocity in microbars per second (brown, dashed) valid at 1200 UTC 24 June 2006. The peaks in the downward vertical velocity (DVV) over the coastal waters and at the immediate coast during the two time periods were -2.6 and -4.4 respectively.

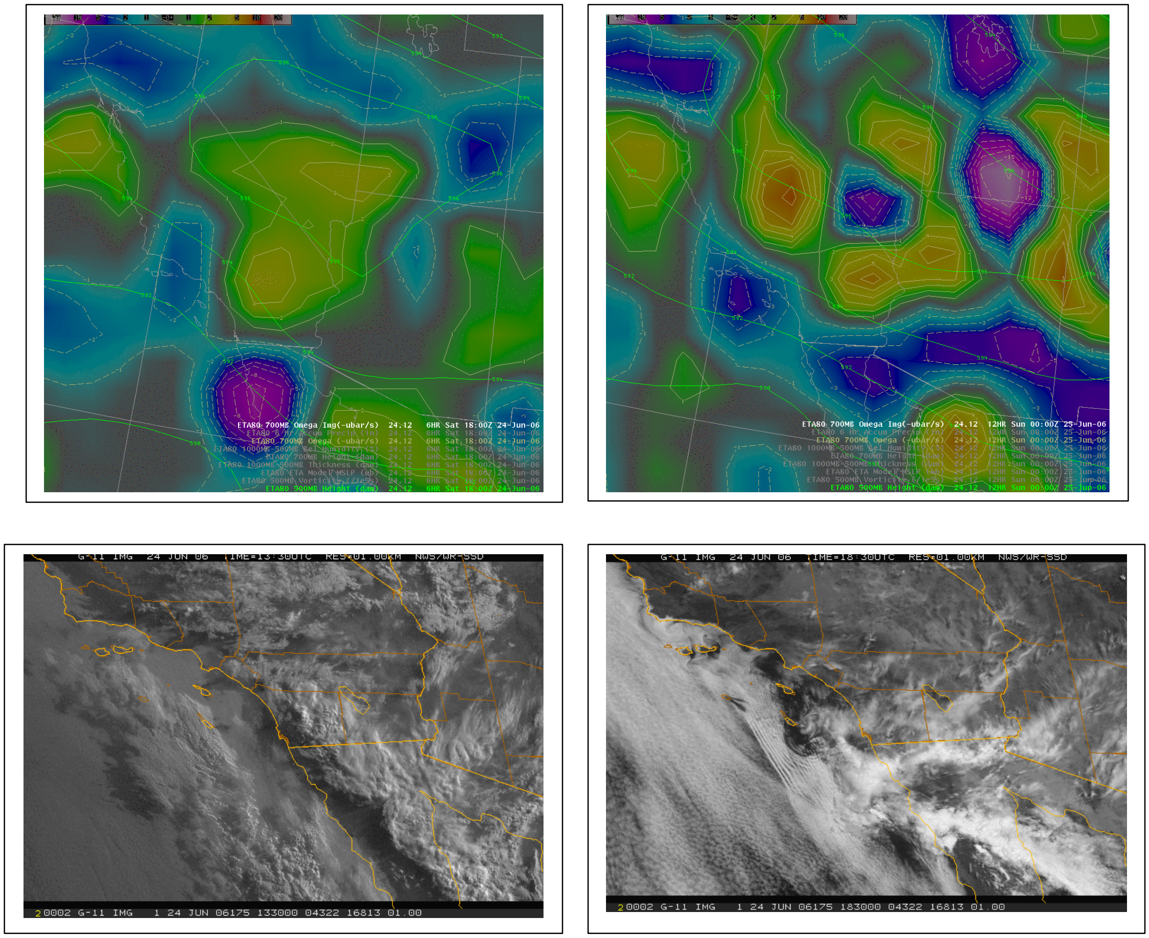

Fig. 8. The subsidence associated with the easterly wave is indicated by the blue to purple region and is moving from east to west across the figures. The upper left is the 06 hour 500 mb heights forecast in decameters (green, solid) and the 700 mb vertical velocity in microbars per second (brown, dashed, and shaded) valid at 1800 UTC 24 June 2006. The upper right is the 12 hour 500 mb heights forecast in decameters (green, solid) and the 700 mb vertical velocity in microbars per second (brown, dashed, and shaded) valid at 0000 UTC 25 June 2006. The lower left is the 1330 UTC 24 June 2006 visible satellite imagery. The lower right is the 1830 UTC 24 June 2006 visible satellite imagery. The peaks in the downward vertical velocity (DVV) over the coastal waters and at the immediate coast during the two time periods were -2.6 and -4.4 respectively. The waves in the low cloud pattern that have been generated by the islands (initially excited by the outflow boundary) appear to be moving westward, even though the clouds moving down the California coast are moving southeastward.

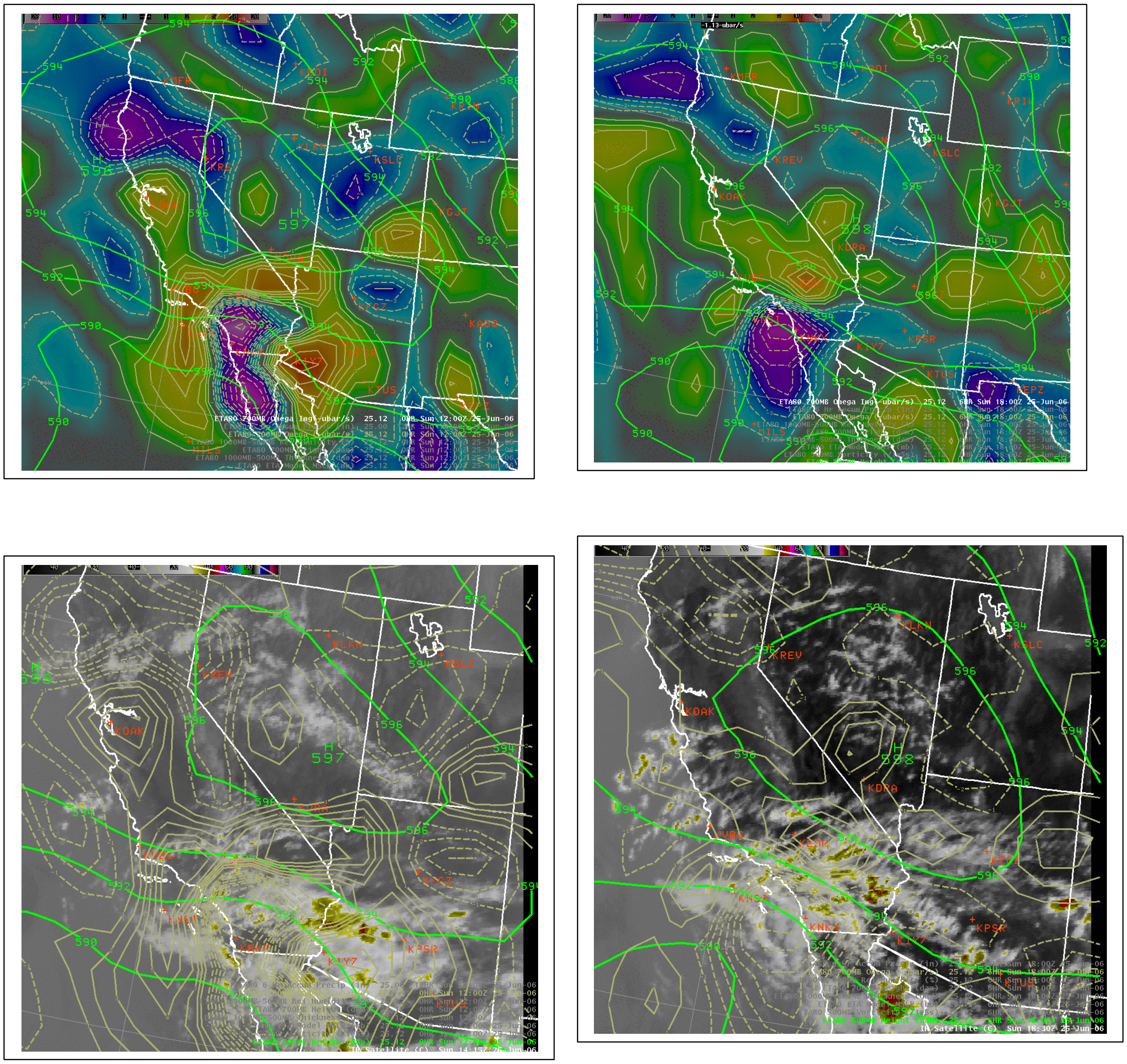

Fig. 9. Upper left figure is the 00 hour 500 mb heights in decameters (green, solid) and the 700 mb vertical velocity in microbars per second (brown, dashed, and shaded) valid at 1200 UTC 25 June 2006. The upper right figure is 06 hour 500 mb heights forecast in decameters (green, solid) and the 700 mb vertical velocity in microbars per second (brown, dashed, and shaded) valid at 1200 UTC 25 June 2006. The lower left is the 1415 UTC infrared satellite imagery overlaid with the 00 hour 500 mb heights in decameters (green, solid) and 700 mb vertical velocity in microbars per second (brown, solid and dashed) valid at 1200 UTC 25 June 2006. The lower right is the 1830z UTC 25 June 2006 infrared satellite imagery overlaid by the 06 hour 500 mb heights forecast in decameters (green, solid) and the 700 mb vertical velocity in microbars per second (brown, dashed) valid at 1800 UTC 25 June 2006. Downward vertical velocities are -16.0 microbars and about -11.5 microbars respectively.

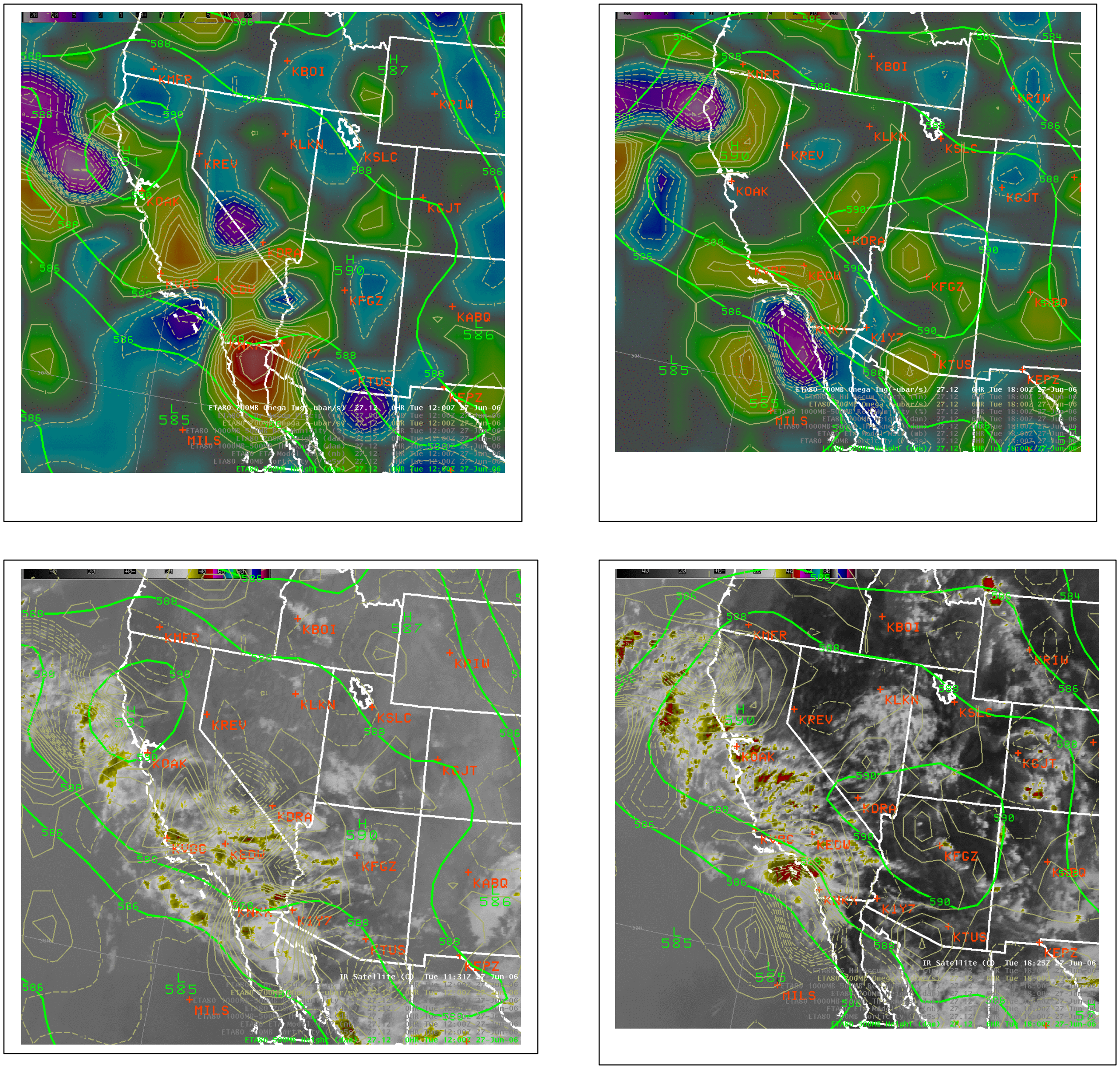

Fig.10. Upper left panel is the 00 hour 500 mb heights in decameters (green, solid) and the 700 mb vertical velocity in microbars per second (brown, dashed, and shaded) valid at 1200 UTC 27 June 2006. The upper right figure is 06 hour 500 mb heights forecast in decameters (green, solid) and the 700 mb vertical velocity in microbars per second (brown, dashed, and shaded) valid at 1200 UTC 27 June 2006. The lower left is the 1131 UTC infrared satellite imagery overlaid with the 00 hour 500 mb heights in decameters (green, solid) and 700 mb vertical velocity in microbars per second (brown, solid and dashed) valid at 1200 UTC 27 June 2006. The lower right is the 1825 UTC 27 June 2006 infrared satellite imagery overlaid by the 06 hour 500 mb heights forecast in decameters (green, solid) and the 700 mb vertical velocity in microbars per second (brown, dashed) valid at 1800 UTC 27 June 2006. The peaks in the downward vertical velocity (DVV) over the coastal waters and at the immediate coast during the two time periods were -5.3 and -12.6 respectively.

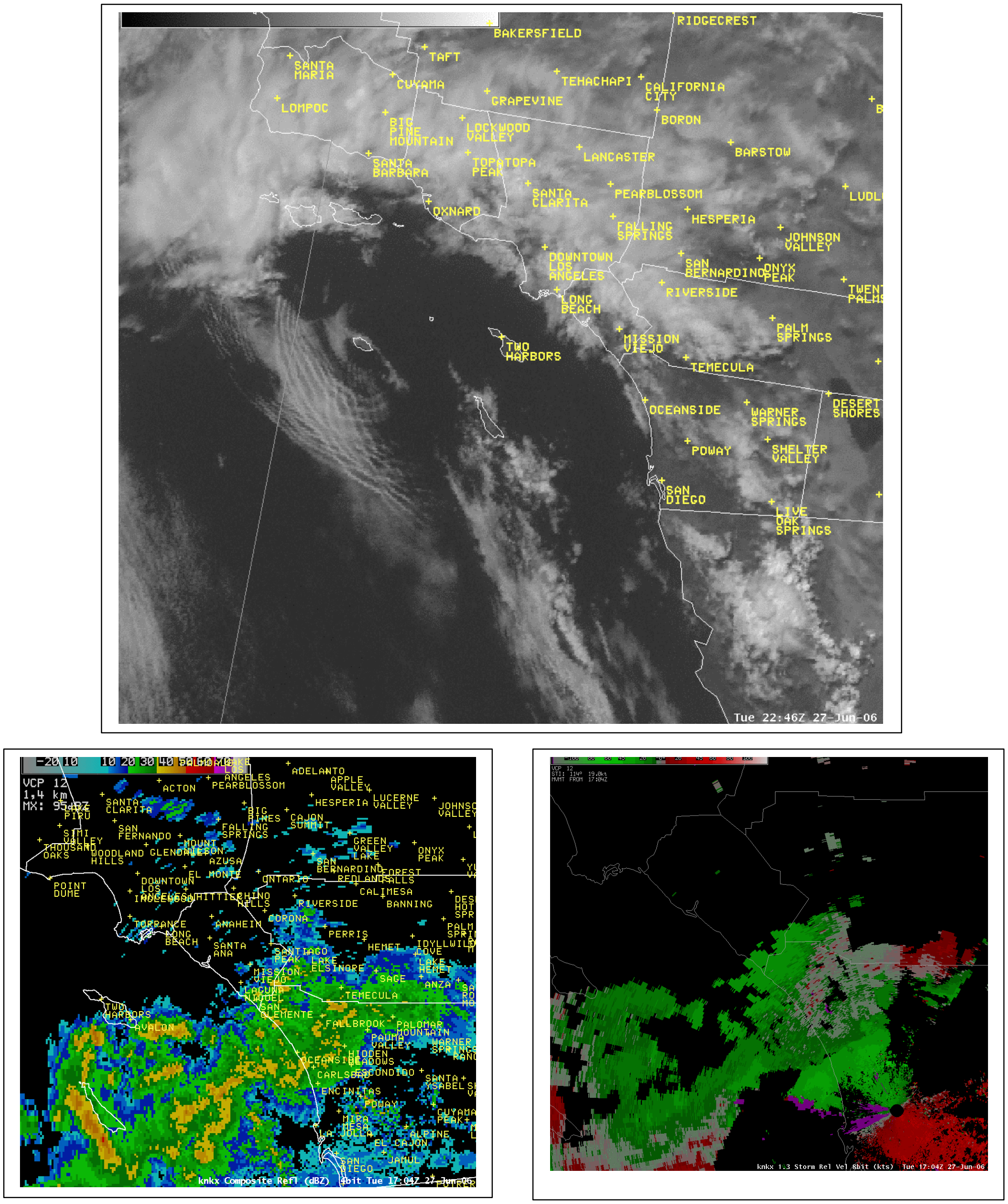

Fig. 11. The upper center is 2246 UTC 27 June 2006 visible satellite imagery. Similar to those seen on 24 June 2006, the waves in the low cloud pattern can be seen radiating away from the islands as the waves move westward. The lower left panel is the 1704 UTC 27 June 2006 KNKX radar composite reflectivity and the lower right is 1704 UTC 27 June 2006 1.3 degree storm relative velocity from the KNKX radar. Winds gusted to about 50 mph with this easterly wave. With the inversion pushed to the surface, weak pressure gradients, and a strong offshore pressure gradient trend this easterly wave brought the heating all the way to the coast.

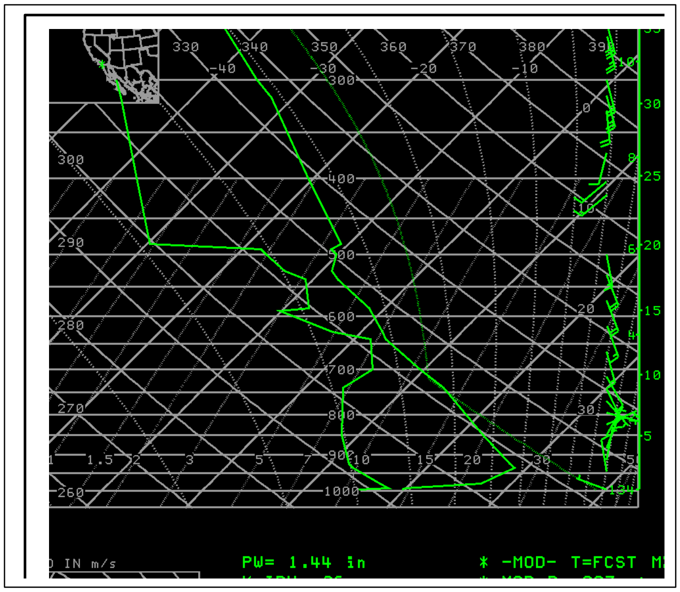

Fig. 12. 1200 UTC 28 June 2008 KNKX sounding showing the mid level southerly (ridge parallel) flow.

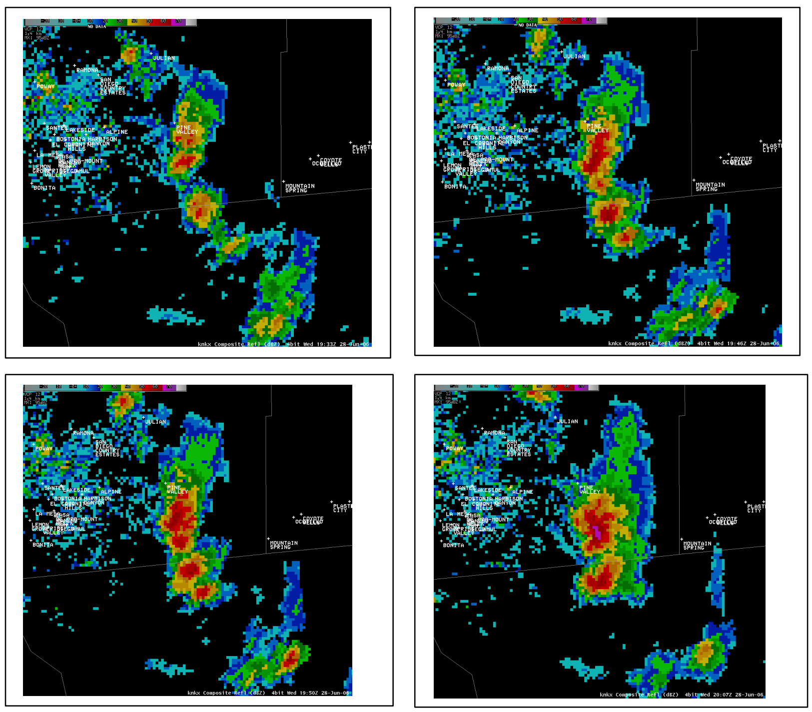

Fig. 13. KNKX composite reflectivity at 1933 UTC 28 June 2006 (upper left), 1946 UTC 28 June 2006 (upper right), 1950 UTC 28 June 2006 (lower left), 2007 UTC 28 June 2006 (lower right). A common valley “convective convergence zone” (shown by the strongest convection), which can easily produce severe thunderstorms is shown creating a very strong thunderstorm. The southerly flow helps to keep plenty of moisture over the heated crest of the mountains as the flow moves along the crest. There is a significant amount of boundary interaction between the “typically stronger thunderstorms” of Northern Baja California and the thunderstorms of the San Diego County Mountains just north of the border.

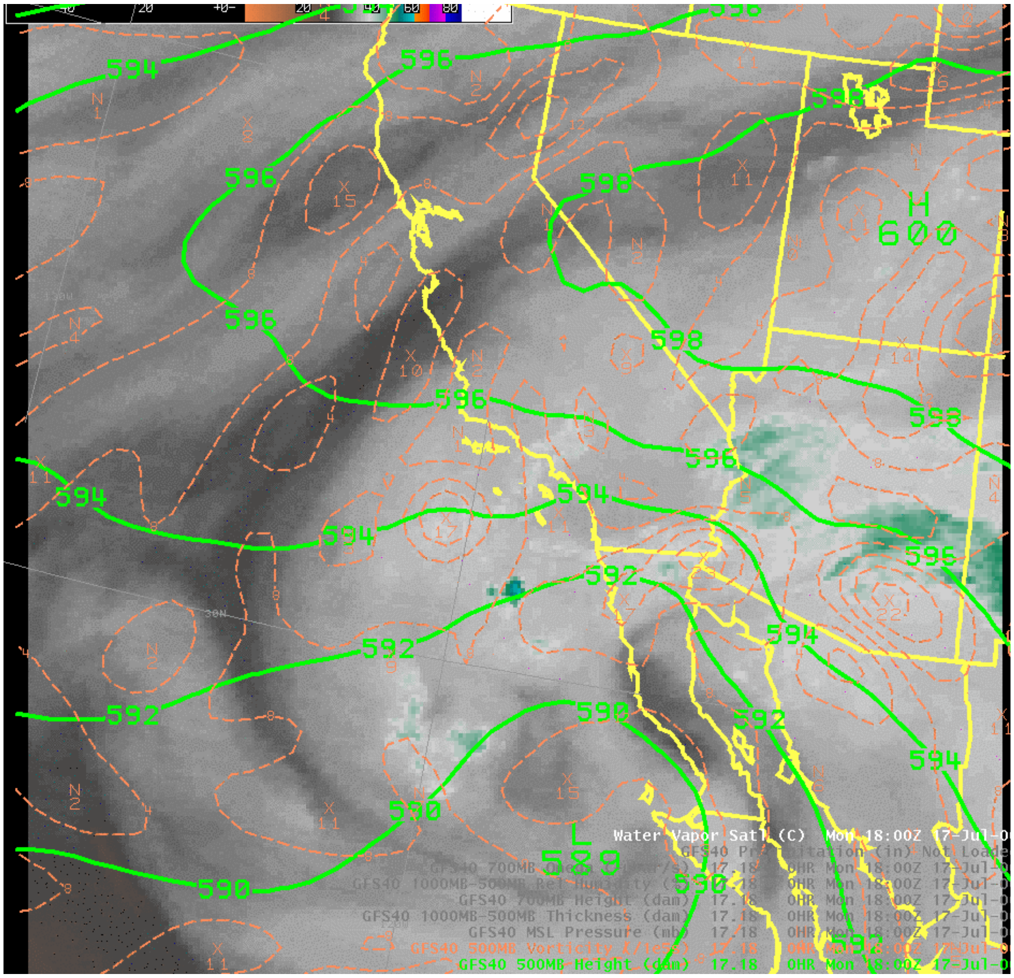

Fig. 14. The 1800 UTC 17 July 2006 water vapor imagery overlaid with the 00 hour 500 mb heights in decameters (green, solid) and 500 mb vorticity (orange, dashed) in s^{-1}. The figure shows a very large upper level low (very large inverted trough in the 500 mb data) moving west under a strong east-west ridge axis with a 6000 meter core. There were several smaller waves rotating around the main low modulating the strength and timing of the convection.

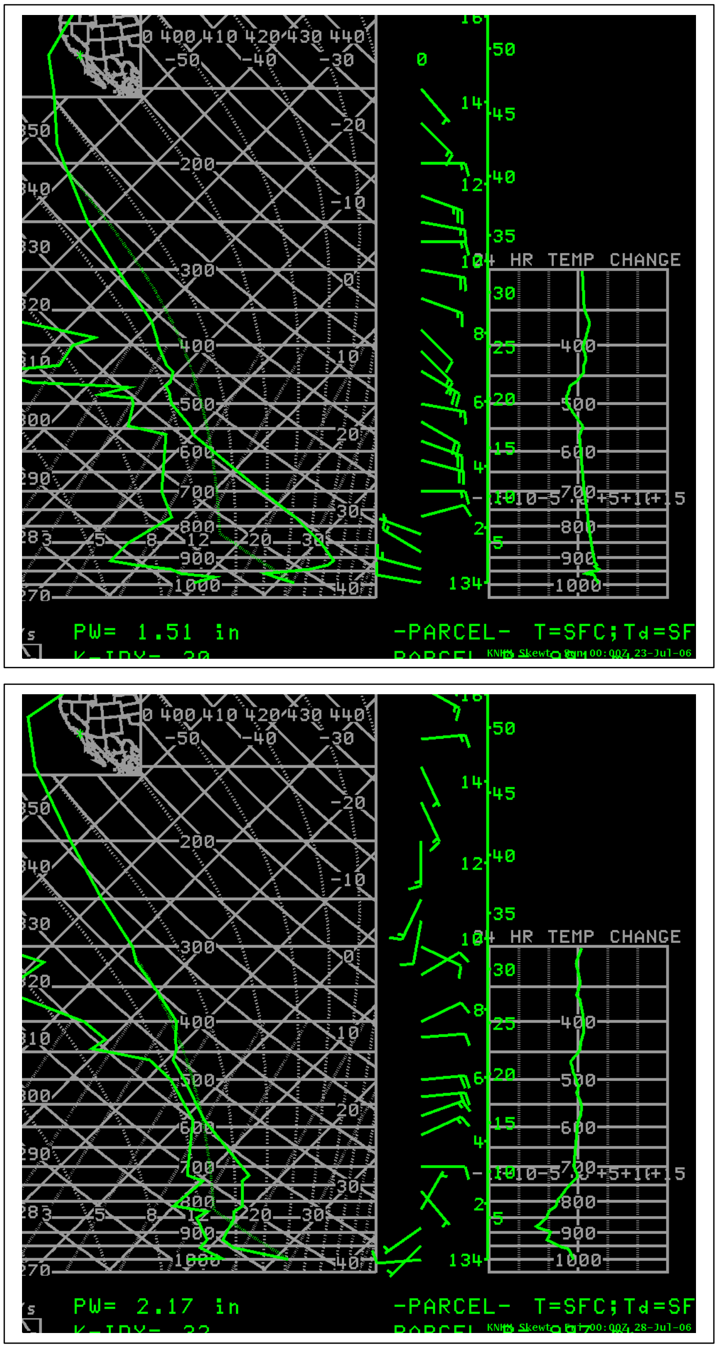

Fig. 15 The upper panel is the 0000 UTC 23 Jul 2006 sounding at KNKX. On this day the temperature topped off at 117 at Riverside (approximately 5 miles southeast of KONT, an all time record). Especially noticeable was the very high temperature at the top of the inversion [around 34.6 degrees C (94 degrees F)]. A severe thunderstorm also occurred, common on such hot days (monsoonal/offshore flow events), especially when early afternoon convection develops on the Santa Ana Mountains or on the Elsinore Convergence Zone in the "Inland Empire". Widespread temperatures from 110 to 120 degrees with easterly flow aloft occurred in highly populated valley areas. The atmosphere changed dramatically by the 0000 UTC 28 July 2006 (lower panel). The boundary layer cooled and became more of a moist, tropical boundary layer, with 850 mb dewpoints approaching 15 degrees C, (prime conditions for well above normal minimum temperatures in the coastal and valley areas).

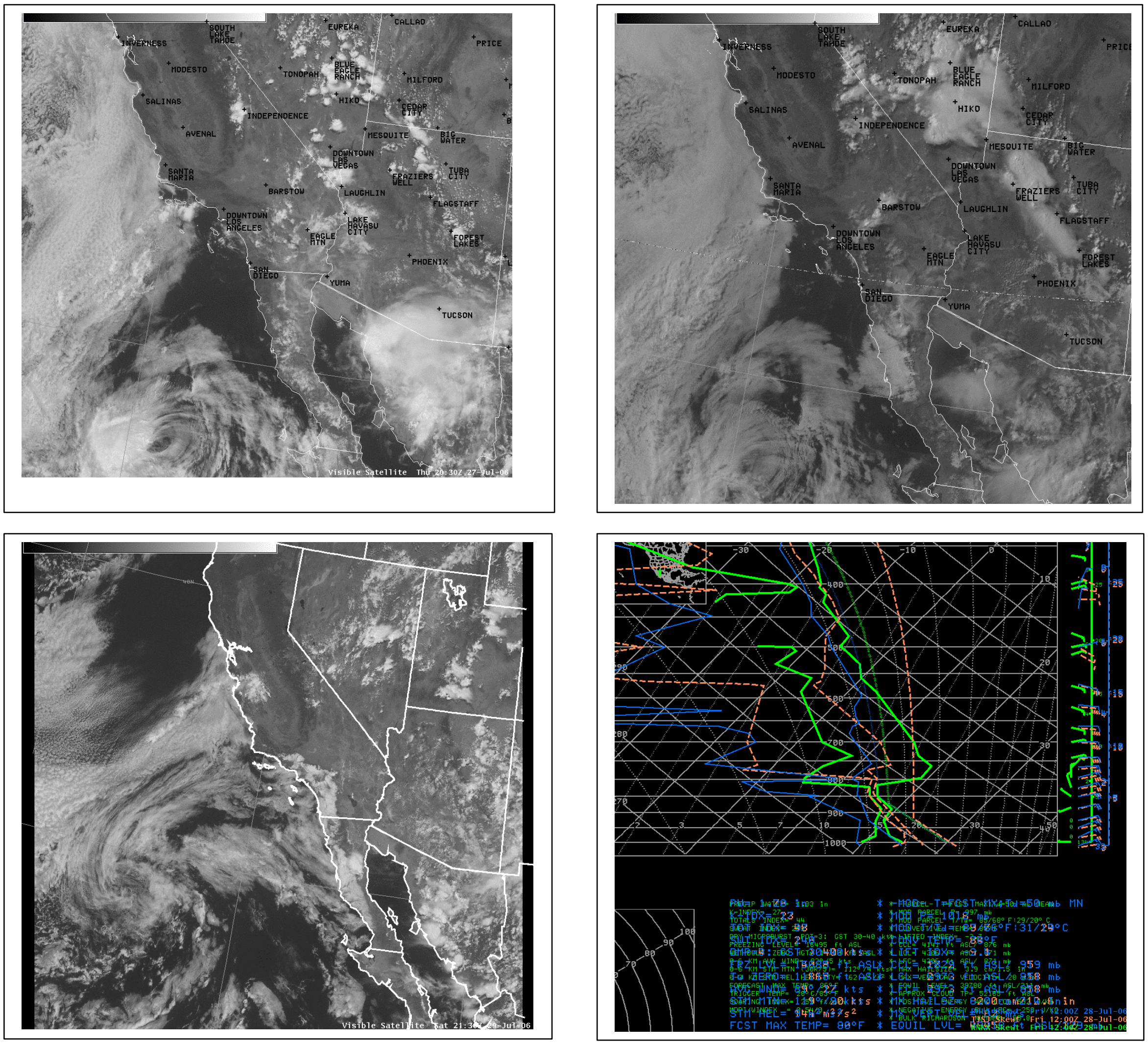

Fig.16. The upper left figure (2030 UTC 27 July 2006 visible satellite imagery) shows former tropical storm Emily. The upper right figure (0000 UTC 28 July 2006 visible satellite imagery) shows the low clouds pushing northward along the coastal slopes of the mountains, (coastal slopes and valleys becoming cloudy first) before expanding toward the coast. The bottom left panel (2130 UTC 29 July 2006 visible satellite imagery) shows the northern arm of the decaying wave producing a tropical boundary layer over the area. The lower right panel is the Miramar (KNKX) sounding (green) near San Diego compared to soundings in San Juan, Puerto Rico (orange) and Kauai, Hawaii (blue) at 0000 UTC at 1200 UTC 28 July 2006 after the tropical airmass of the decaying tropical storm moved in. Notice the similar heights of the tropical inversions. The airmass under the tropical inversion is actually warmer and wetter at San Diego than at Kauai. The Miramar sounding shows a slight bend at about 900 mb reflecting a weak, lower inversion, which should normally be watched for re-development of a lower, more typical inversion and associated low cloud deck. The air mass was nearly saturated up to about 6000 feet, resulting in scattered measurable rain. There is easterly (trade-wind like) flow throughout much of the sounding, similar to that found in the two tropical locations. The persistent low cloudiness eventually resulted in a record high minimum temperature at Newport Beach on 31 July 2006, with numerous sites reporting record <u>low</u> maximum temperatures on that same day! This is in contrast to the strong offshore winds and offshore gradients that occur when tropical depressions with deeper low centers approach the area (and generally result in record <u>high</u> maximum temperatures).